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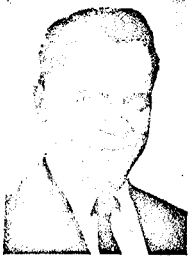
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EXPERIENCE IN THERMAL-VACUUM TESTING EARTH SATELLITES AT
GODDARD SPACE FLIGHT CENTER

By: A. R. Timmins and K. L. Rosette



A.R. Timmins



K.L. Rosette

Mr. Timmins received his B.S. in Chemical Engineering at the University of Pittsburgh in 1937. Additional training was received at Bowdoin College, Massachusetts Institute of Technology, and the University of Maryland. He was formerly associated with the Jones and Laughlin Steel Corporation in the Metallurgical Department. Subsequently, he served in the U. S. Navy, and later joined the Naval Ordnance Laboratory as a member of the Test and Evaluation Department. Since 1960, he has been in charge of the Thermal-Vacuum Test Section, Test and Evaluation Division, at the Goddard Space Flight Center.

Mr. Rosette received his B.S. in Mechanical Engineering at Virginia Polytechnic Institute in 1960. He is presently doing graduate work at the Catholic University of America in Washington, D. C. He has been employed at the Goddard Space Flight Center since July, 1960, as a member of the Thermal-Vacuum Test Section of the Thermodynamics Branch. He is a member of Pi Tau Sigma, Tau Beta Pi, and the ASME.

INTRODUCTION

High system reliability is a prime requirement for an effective space program. This requirement is underscored by the high cost of the launch vehicles and spacecraft. Early estimates indicate the average cost per pound of material in orbit results in an investment of about \$67,000. ^{1/} Furthermore, since launch opportunity for certain space studies is dependent upon interplanetary relationships, success on the first launch attempt is necessary in order to effect timely acquisition of needed space data. Thus, assurance of success must be enhanced by every possible means. One of the most effective techniques to enhance ^{1/} NASA TN D-1340, "Scientific Satellites and the Space Environment", J.C.New, GSFC

reliability of our space systems has been the application of laboratory tests which simulate, in so far as practical, the many environmental conditions actually encountered by the spacecraft. Environmental tests must be applied in a well defined test program which gives proper attention to the test levels, test duration, sequence of application, and appropriate evaluation of results. The specifications for such tests involve consideration of ground handling, launch, injection and orbital environs. At the start of the space program, evaluation experience with space hardware was limited to that obtained from research sounding rockets, weapons systems, and missile testing. While this experience provided a foundation for environmental specifications covering ground handling and launch, little foundation was available for the orbital space environs. Facility limitations prevented duplication of the effects of the more exotic of the space environs (such as micrometeorites and energetic particles) on a complete satellite. These environments were more properly evaluated on a material or subsystem basis. For the complete spacecraft thermal-vacuum tests were used to evaluate the performance under simulated space conditions. These tests gave information on the performance at expected orbital temperature extremes, the adequacy of the thermal design, and on the failure rate versus time.

A number of scientific earth satellites have been tested, and launched by the Goddard Space Flight Center. A review of the specifications, laboratory test results and orbital performance of the spacecraft should be profitable in determining the adequacy of some aspects of the specifications used. This report will be restricted to the Thermal-Vacuum test experience and analysis related to three Scientific Satellite projects. It will discuss the choice of parameters, the philosophy used, and the experience gained by the Test and Evaluation Division of the Goddard Space Flight Center.

TEST PHILOSOPHY

The test philosophy ^{2/} employed has been to use environmental tests to gain information from which the suitability of a spacecraft for flight can be assessed. To this end, the systems test program for a satellite has six goals:

1. Verification that novel or unproven designs meet performance requirements and have a satisfactory life expectancy.

^{2/} The Role of Environmental Testing in Satellite Reliability. May, 1962, J.H. Boeckel, GSFC No. X-320-62-41.

2. Verification that particular samples of previously employed hardware are suitable in a new application.
3. Elimination of defects in design, material or workmanship (i.e. finding the weak links in the chain).
4. Discovery of unexpected interactions between sub-assemblies when the system is exposed to environmental stress.
5. Training of personnel who will be responsible for the satellite at the launching site and those who will be responsible for data reduction and analysis.
6. Generation of information which will serve as a guide in making new designs and in assessing their reliability.

The degree to which these goals may be attained is strongly conditioned by the fact that in typical programs, only one prototype and two flight spacecraft are available for test.

In attempting to reach the goals, despite the limitations, one must formulate a model of the failure pattern which we might expect to encounter and base the test philosophy on this concept. Our somewhat limited experience suggests that satellite failures fall into four categories:

1. Early failures caused by a major design weakness.
2. Early failures resulting from defects in material or workmanship.
3. Random failures whose frequency of occurrence is a function of design and quality control.
4. Wear-out failures.

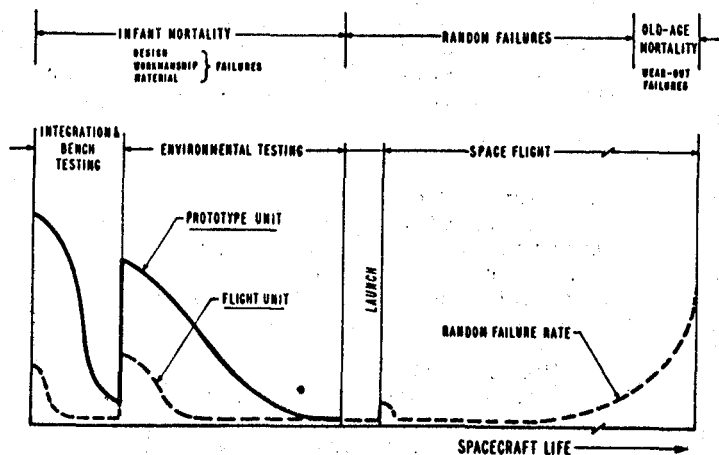


Figure 1. Failure Pattern

Figure 1 illustrates this model pattern. If the failure pattern is applicable, progressive improvement in the dependability of the system should occur during the test program. As the "weak links" in the subsystem chain are found and strengthened, the curve should approach the random failure rate level. The length of time necessary to reach this level is vital and elusive. Consistent with the locating of weaknesses is the practice of providing a margin of safety over expected extremes of operation. To this point, prototype spacecraft are subjected to more severe environmental stress than flight models. In the thermal-vacuum tests, prototype model spacecraft are subjected to temperature extremes 10°C in excess of those predicted for orbit. Flight models are subjected to thermal-vacuum tests at predicted orbital temperature extremes.

For this philosophy to be workable, an extensive program of part qualification on the basis of tests or, previous successful utilization must be presupposed. Similarly, sub-assembly testing under environments more severe than those expected in actual use is a near necessity. (It should be noted that the difficulty of conducting adequate sub-assembly tests of complicated new devices on the time scale of the typical satellite development program is frequently overwhelming. If not accomplished, however, a risk is incurred that the system test may be unnecessarily interrupted or extended by the sub-assembly failure).

SPACECRAFT TESTED

The data developed in this report is based upon the experience gained in testing three spacecraft. These were: (a) Explorer X, the Interplanetary Probe (one prototype and three flight models), (b) Explorer XII, The Energetic Particles Satellite (one prototype and two flight units), and (c) Ariel I, the International Ionosphere Satellite (one prototype and two flight units). Figures 2, 3, and 4 show these spacecraft.

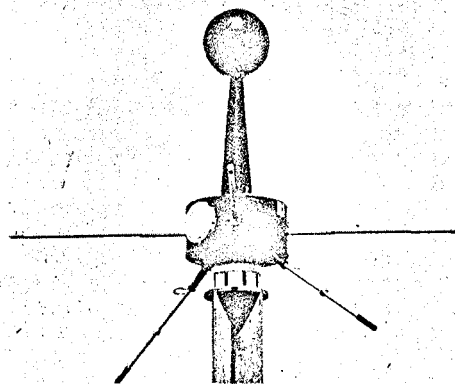


Figure 2. Explorer X, the Interplanetary Probe

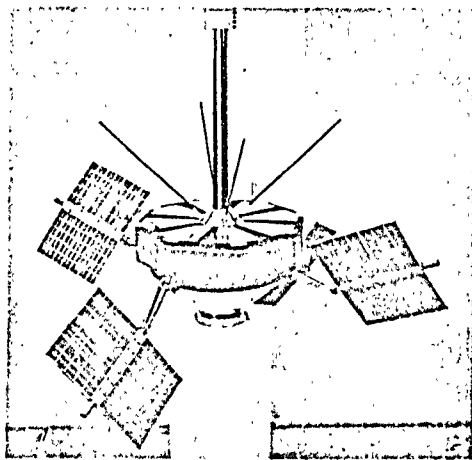


Figure 3. Explorer XII, the Energetic Particles Satellite.

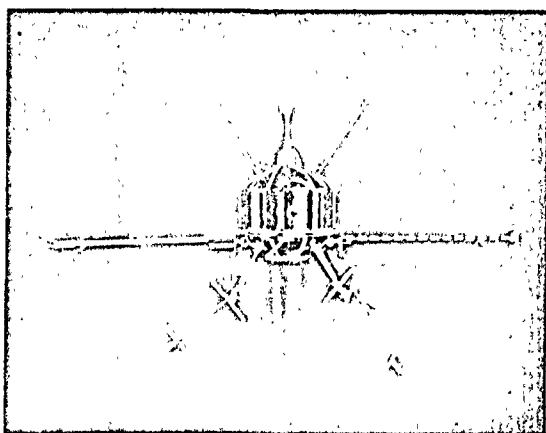


Figure 4. Ariel I, the International Ionosphere Satellite

DESCRIPTION OF TESTS CONDUCTED

The tests conducted were accomplished in thermal-vacuum chambers having a vacuum capability of 1×10^{-5} mm Hg or better. The thermal control in most cases was accomplished by control of the chamber walls. Additional thermal gradient tests were conducted using tungsten lamps to control local temperatures of a sector of the spacecraft while the chamber was used to control the temperature of other portions of the spacecraft (at a different temperature). These tests were conducted to determine if any weaknesses existed when high thermal gradients existed within the spacecraft corresponding to a particular orientation of the spacecraft with respect to the sun.

The temperature capabilities of the chambers were -65°C to $+100^{\circ}\text{C}$. Solar simulation was not available for any of the tests reported herein. The three types of tests used were: cold soak test, hot soak test, and temperature gradient test. Table 1 shows the scheduled test duration for each spacecraft.

	Hot	Cold	Gradient	Total
Explorer X				
Prototype	1.25*	1.25*	--	2.5
Flight Units	1	1		2
Explorer XII				
Prototype	2	2	4	8
Flight Units	-	1	4	5
Ariel I				
Prototype	3	2	2	7
Flight Units	3	2	-	5

* Half of battery life

Table 1. Scheduled Test Times. (Days)

LABORATORY TEST RESULTS

The data presented in this report have been arranged to examine essentially two aspects of failures encountered in the conduct of the thermal-vacuum tests. These two are: (1) Effects of high versus low temperature, and (2) The failure rate for both the high and low temperature levels. A word of explanation is necessary on what constituted a failure. A severe criterion was used, that is, any malfunction which caused sub-standard performance or loss of data was classed as a failure. This, of course, is not synonymous with satellite or even experiment failure.

The data is organized in accordance with the following criteria: - Examination of the test results must be made with these rules in mind.

1. Time to failure is satellite (or subsystem) operating time under vacuum (conditioning time under vacuum was not counted).
2. Time to failure for any subsystem which did not have a continuous duty cycle was the operating time of that subsystem.
3. Time to failure for any hot test does not include any time under the cold test environment. Similarly, for the time to failure classified as a cold test failure.
4. Time to failure for any sub-system which was retested was the total operating time of the sub-system except for the case where the same component failed.
5. Failures which occurred during chamber evacuation on retests were counted as early failures. (For example, if a corona type of failure occurred on a retest of the spacecraft, the time to failure did not include the duration of the original test).
6. The operating time of the spacecraft in the thermal gradient type

of test is included in the failure rate curves. The failures are identified as hot or cold, depending upon conditions at time of failure.

Spacecraft	Type of Test				Totals*
	Hot		Cold		
Prototype					
Explorer X	4		0		
Explorer XII	6	24	4	15	39
Ariel I	14		11		
Flight Units					
Explorer X	2		6		
Explorer XII	0	5	11	28	33
Ariel I	3		11		
Totals *		29		43	72

* Totals do not include set-up, corona, or operator failures.

Table 2. Summary of Failures in Thermal-Vacuum Tests.

TYPE SYSTEM	TEST	MECH. 2/	COM- PO- NENT	DE- SIGN 3/	THER- MAL 4/	TOTALS
Proto- type	cold	2	7	3	3	15
	hot	6	9	2	7	24
Flight	cold	4	10	9	5	28
	hot	0	1	2	2	5
TOTAL	cold	6	17	12	8	43
	hot	6	10	4	9	29
Grand Total		12	27	16	17	72

1/ Does not include set-up, corona or operator failures.

2/ Mechanical failures include cold solder joints, connectors, sheared screws, and broken leads.

3/ Design failures include underrated components and unbalanced circuits.

4/ Thermal failures include inadequate heat sinks, poor thermal contacts, and temperature sensitivity.

Table 3. Summary of Types of Failures 1/

SPACE-CRAFT	ITEM	EXPOSURE TIME (DAYS)	2/	DEFECT
Ariel I (Flight Unit)	Solar array protec- tive circuit	C 4	R	Circuit would not operate
Ariel I (Proto- type)	Electron Density	C 6	R	Temperature Sensitive
	Solar Array Shunt Regulator	C 7	N	1 Megacycle sine wave pre- sent when cir- cuit operating
	Optical Aspect	C 9	N	Voltage spikes
	Tape Recorder	C 11	R	T.R. did not playback on command-

continued

SPACE-CRAFT	ITEM	EXPOSURE TIME (DAYS)	2/	DEFECT
Ariel I (Proto- type) con- tinued	Tape Recorder	H 5	R	Excessive current for tape recorder
	Recycle Timer	H 6	N	Spacecraft did not turn on after undervoltage test.

1/ Long term defined as 4 days or greater.

2/ Kind of Failure: N= New Failure; R= Repeat Failure, C=Cold test; H= Hot test

Table 4. Table of Long Term 1/ Failures.

SPACE-CRAFT	HIGH TEMP.	LOW TEMP.	SOLAR ASPECT	
Explorer X				
Proto- type	+35°C & 43°C*	0°C & 25°C*	This type of test did not apply	
Flight Units 1 & 2	+20°C & 40°C*	0°C & 30°C*	*Stabilized temp- erature of Bias Sphere	
Explorer XII			45°	135°
Proto- type	+35°C	-10°C	+45°C(1) -20°C(2)	+35°C(2) -20°C(4)
Flight Units 1 & 2	See 45° Aspect	-10°C	+32°C(3) -20°C(2)	+35°C(2) -10°C(4)
Ariel I			30°	135°
Proto- type (1) (2) (3)	55°C 47°C 42°C	-10°C -10°C -15°C	+30°C(4), +10°C(4)	
Flight Units 1 & 2	37°C	-8°C	This type test not conducted	
			(1) Test No. 1 (2) Test No. 2 (3) Test No. 3 (4) UCL Electronics Stack 2	

Table 5. Summary of Thermal-Vacuum Test Parameters for Three Spacecraft

Table 2 summarizes the failures for both prototype and flight unit spacecraft with respect to the thermal environment. Table 3 is the same information, but segregated according to the type of failure. Table 4 is additional detail on failures which occurred after 4 days of testing. Table 5 lists the temperature levels which were used for the testing of the three spacecraft.

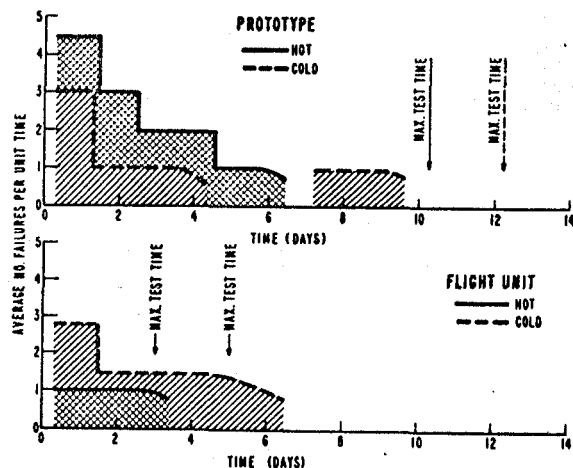


Figure 5. Summary of Spacecraft Failures versus Time in Thermal-Vacuum Tests.

Figure 5 depicts failures versus time information. Failures of prototype and flight spacecraft tests are presented separately, and in each case, shows the influence of the hot and cold environments.

DISCUSSION

High vs Low Temperature Failures: The terms "high" and "low" temperatures have been used in a general sense. Table 5 lists the actual temperatures used in testing the spacecraft. It shows that "high" temperatures ranged from 20°C to 55°C while "low" temperatures ranged from 0°C to -15°C. Table 2 shows that the high temperature level produced more failures on the prototype spacecraft than the low temperatures. With these failures corrected (and with a slightly lower temperature level used) the total number of high temperature failures on all the flight unit spacecraft was reduced to five. This was expected and is consistent with the philosophy of testing used.

The data on low temperature tests show more failures in flight spacecraft than on prototype spacecraft. These results were not expected. Examination of the failure results indicates approximately 40% of the failures were repeat failures, i.e. the same item had caused a failure before. This trend indicates prototype failures should be examined carefully for other potential failures and a repaired item should be completely requalified before reentering the system. Another 40%, which could not be related to previous failures, were evident in less than 24 hours of testing. The remaining 20% were new type failures and appeared after 2 to 9 days of exposure to the cold environment.

Types of failures: Table 3 summarizes the types of failures. Component (resistor, capacitor, transistor, etc.) failures account for 35% of the total. Mechanical, design, and thermal categories are the other major types of failures. This table gives further detail on the excessive number of cold failures on flight spacecraft. It shows 65% of these failures were in the component and design categories.

Long term failures: During laboratory tests, one prototype spacecraft had several problem areas which required retests of the entire spacecraft. The test time amounted to 12 days at low temperatures and 10 days at high temperatures. This gave an opportunity to disclose failures which might occur if testing time was increased beyond the present 8 to 10 days for prototype spacecraft, (seven at high temperature and three days at low temperature).

Table 4 shows that 55% of the long term failures were repeat failures, i.e., the same item had shown trouble previously in the test. The results verify the need for full time testing after repair of an item. There is always a temptation to shorten the time for a retest, but the temptation should be resisted.

The failures listed as new failures in Table 3 must be examined carefully. These are data which may be helpful in affirming or revising the test duration specified for thermal-vacuum tests of prototype and flight spacecraft. Two of the failures, one at 7 days and one 9 days, occurred during a cold test on a prototype spacecraft. Although listed as failures, there was no malfunction or loss of data; in each case, it was interference in the signal output. Another failure, after 6 days of operating time, occurred in a hot test on a prototype spacecraft. This failure was important since it would have resulted in a Satellite failure at the time the recycle timer was required to work. (It should be noted, however, that the recycle timer does not operate continuously, but only at times that the battery supply voltage decreases to a predetermined level. The cause for this failure could have been influenced more by the number of times the unit was actuated, rather than the time under vacuum).

Most of the failures listed in Table 4 may be analyzed as to importance or effect on spacecraft performance. Such an analysis shows that no in-line subsystems are involved and total spacecraft operation is not jeopardized. However, it is interesting to note that all of the reported long term failures were from three models of spacecraft out of a total of 10 which were tested for the three

projects. The test duration for the other spacecraft tested was 3 days or less, at the high or the low temperature level. It would appear that additional long term testing of both prototype and flight unit spacecraft is in order to gain additional data on this subject.

FLIGHT PERFORMANCE

Brief commentaries on the flight performance of each of the three spacecraft are given below. The scientific findings and detailed performance reports are covered in other publications.

The Interplanetary Probe (Explorer X) was launched on March 25, 1961. Its transmitters functioned for the expected life of the spacecraft (60 hours). One failure was encountered. Temperature measurements inside the sphere which housed the rubidium vapor magnetometer showed a continuous rise for several hours after satellite injection. When the temperature rose above 55°C after 2 hours, the rubidium vapor magnetometer operation became intermittent. Post-flight tests demonstrated that during launch out-gassing of the hot nose cone surface adjacent to the sphere caused deposition of a film on the sphere that greatly increased the absorptivity of the surface. This caused the temperature to be higher than predicted.

The Energetic Particles Satellite (Explorer XII) was launched from Cape Canaveral August 15, 1961. Operation of the satellite ceased abruptly at 1:12 EST on December 6, 1961 after 112 days of operation. All experiments functioned perfectly during its orbital life. The exact cause of the failure has not been determined.

The International Ionosphere Satellite (Ariel I) was launched from Cape Canaveral on April 26, 1962. The Lyman alpha experiment failed on launch. Otherwise, operation of the spacecraft was perfect until July 12, 1962, at which time the system began to go into 18 hour periods of under-voltage. As of December, 1962, Ariel I had a total equivalent operating time of 127 days. The spacecraft was continuing to send good scientific data approximately one third of the time. The intermittent operation was attributed to degradation of the Solar Array and other damage caused by the Enhanced Radiation Belt which resulted from the high altitude nuclear detonation which occurred on July 9, 1962.

Failure Rate - Laboratory Test and Flight

The model curve shown in Figure 1 indicates that the number of failures during laboratory tests should decrease with time until we reach some random failure rate. It postulates also, different failure rates for prototype and flight unit spacecraft. It does not deal with the effect of temperature level on the

failure rate.

It is of interest to see how the laboratory test data reported herein compares with the model curve. The data did not permit generation of a curve to predict the time at which a random failure rate is attained. However, the limited data were used to prepare Figure 5. This figure, although restricted to thermal-vacuum tests, can be examined with respect to the environmental testing part of the model curve. The difference in failure rate between the prototype and flight units for the high temperature test is in agreement with that postulated by the model curve. The low temperature test results (failure rate for prototype versus flight units) are not in agreement with those postulated from the model curve. Figure 5 also presents information on the effect of temperature level on failure rate. The figure shows both the high and low temperature tests starting simultaneously at zero time. This is not possible, of course, but is presented in this manner to have some basis for comparability for the three satellites (the satellites had different test duration, different amounts of retest, etc.). The results, especially for the prototype spacecraft, indicate that the two temperature extremes should be considered as separate failure rate curves.

The curves in Figure 5 may be useful in judging the performance of a spacecraft during thermal-vacuum testing. The curves are considered a best estimate of failures versus time for a typical satellite. Performance better than the levels shown would be encouraging for predicting successful space performance. Performance worse than the levels shown would be reason for concern and for extending test time.

The flight performance of the three spacecraft has, in general, been quite satisfactory. Failures in two of the spacecraft (Explorer X and Ariel I), were of a type not covered in the thermal-vacuum tests. The Explorer XII failure, after approximately 4 months, may have been detected had longer term and more severe thermal-vacuum tests been conducted.

The laboratory and flight data presented are insufficient to form any firm test times. However, some useful estimates can be made, such as:

Recommended time to test (hot) 6 days
prototype spacecraft (cold) 4 days

Recommended time to test (hot) 4 days
flight unit spacecraft (cold) 4 days

The above estimates discount the failures shown at 7-9 days on prototype spacecraft.

This point requires clarification by additional data. The above estimates compare, respectively, with presently used test duration of 7, 3, 3, and 2 days.

LIMITATIONS OF DATA

An important point with respect to interpreting the failure data is the lack of complete sub-assembly testing, and use of unproved components. These programs were often forced by firm launch dates to use partially proven components and/or sub-systems. Principal difficulties in trying to use the laboratory failure rate data from system tests to predict long term satellite orbital performance is that conventional statistical methods require tests on many samples so that distribution curves may be generated and used in establishing probability levels. At present, there are insufficient performance data and hence no satisfactory method for determining conclusive probability figures. The data reported herein do not justify, at the present time, the use of an exponential decrease in failure rate as a basis for mathematically determining a reliability figure with statistical confidence. Cooperative effort now being applied throughout the space industry will, in time, establish conclusive data on mean time between failures for components operating in the space environment. These data, coupled with failure data from the system tests, will permit more accurate prediction of the probability of successful performance of the spacecraft for its specified design life.

CONCLUSIONS

The data presented are not sufficient in number to indicate more than a trend which may be useful in establishing test parameters and time durations for the conduct of thermal-vacuum testing of earth satellites. Also, these data do not include any experience in which solar simulation tests were conducted. Recognizing these limitations, the following points are offered.

1. The philosophy and test programs carried out on three earth satellites have been helpful in attaining generally successful performance in space.
2. The cause of the premature failure (3 to 4 months operation instead of one year) of one spacecraft is not fully known.
3. Although the data reported shows some similarity to a model exponential decrease in failure rate with time under thermal-vacuum test, the results are neither

consistent nor extensive enough to justify using an exponential curve as a basis for computing performance probability.

4. Susceptibility of spacecraft to failure from high versus low temperature environments varies between spacecraft, but experience to date indicates additional time should be considered for the low temperature environmental phase of the test.
5. Duration of prototype thermal-vacuum tests should be extended to at least 10 days (operating time). Six days at the maximum temperature level and four days at the minimum temperature level is recommended.
6. Duration of flight unit thermal-vacuum tests should be extended to at least 8 days. Four days at the maximum temperature level and four days at the minimum temperature is recommended.
7. The $\pm 10^{\circ}\text{C}$ margin used for prototype spacecraft testing should be continued.